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REAL RAINFALL TIME SERIES FOR STORM SEWER DESIGN

by

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ABSTRACT

This paper describes a simulation method for the design of retention storages, overflows etc. in storm sewer systems. The method is based on computer simulation with real rainfall time series as input and with a simple transfer model of the ARMA-type (autoregressive moving average) applied to a storm sewer system. The output of the simulation is the frequency distribution of the peak flow, overflow volume etc. from the overflow or the retention storage. The parameters in the transfer model are found either from rainfall/runoff measurements in the catchment or from one or more simulations with an advanced hydraulic computer model.

INTRODUCTION

Since the first computer models for storm sewer simulation were introduced nearly twenty years ago, intensive effort to improve the models has taken place. As a result of this impressive work carried out by some of the best researchers in the world in the field it is now possible to simulate the flow in complex systems of pipes, manholes etc. by numerical models, which include all the elements of the basic hydrodynamical equations for one-dimensional unsteady flow. When computer capacity increases significantly in the next decade, it is expected that these models will be used very commonly in the design of storm sewer systems.

For several years it has been a general practice to use the peak flow for a given return period as the design criterion for the various structural elements in storm sewer systems. However, several examples can be given where the peak flow is not the most suitable design parameter. Take, for instance, the discharge from an overflow to a small lake, for which the total overflow volume could be a more relevant parameter than the peak flow. Due to the complex relation between the rainfall and overflow discharge, it is not possible to establish a connection between peak flow and overflow volume. Therefore, a real rainfall time series is used as input for simulation if a unique statistical output is desired.

Combining advanced hydraulic computer models and long time series of real rainfall is not presently a practical and economical tool in storm sewer design. The aim of this project was to present a simplified method, which approximated the behaviour of the sewer system with

reasonable accuracy and which, moreover, was simple enough to permit real time series to be used as input. It is important to emphasize that the method here suggested is not intended to present any definite and sophisticated solution. The main emphasis has been placed on simplicity and statistical consistency.

RAINFALL TIME SERIES

The rainfall time series used in this project was recorded in Gentofte, a suburb north of Copenhagen, in the period from 1933 to 1962. Only rainfalls in the summer, May to October, were included and only rainfalls greater than 3 mm were used. In all, the time series consisted of approximately 1100 rain events. The data was a part of a greater Danish rainfall data base, which is now being compiled by SPILDEVANDSKOMITEEN (Danish Committee of Sewer Systems). Further details about the data are reported by Johansen (1978).

A plot of part of the rainfall time series is seen in Fig. 1. The rainfalls were arranged as a one-dimensional time series where the rainfalls were separated by a fixed dry weather period of the shortest possible duration in relation to the time scale (delay) of the sewer system, including the retention storage. In the example shown in this paper, a dry weather period of 3 hours was used.

SURFACE LOSSES

A simple surface model was used in the project. The model removed the first part of the rainfall as depression storage. Furthermore, the model was based on the assumption of a fixed relation between rainfall intensity and surface runoff. The depression storage was only taken into account if the time between two succeeding rainfalls was less than 2 hours. Since the data file also included some sporadic rain of less than 3 mm, it was possible to reduce the depression loss by the volume of sporadic rain which occurred less than an hour before the real rainfall started.

In this study, the dynamic behavior of the surface process was not modeled separately, but was part of the general transfer-model mentioned below.

ARMA-TRANSFORMATION

The basic assumption that the total runoff process can be described as a linear transformation of net rainfall time series is fundamental to this approach. As a consequence of the linearity principle, the superposition principle is valid and the well known hydrograph analysis can be used.

From the theory of hydrographs it is known that the output from the catchment $Q(t)$ is found from the input, the hyetograph $I(t)$, by the convolution integral

$$Q(t) = \int_0^t u(t-\tau)I(\tau)d\tau \quad (1)$$

The function $u(t)$ is the so-called instantaneous unit hydrograph. This $u(t)$ can be determined from known series of $Q(t)$ and $I(t)$ applying the Wiener-Hopf expressions (see e.g., Yevjevich, 1972) or by Fourier transform.

The disadvantage of using a numerical instantaneous unit hydrograph for simulation is that the number of calculations at each time step is large. Thus, for the purpose of transforming very long series, a simpler method would be suitable.

In hydrology different types of filtering techniques such as the moving average, linear reservoirs, and first-order autoregressive filter have been used for many years. During the last decade, ideas have concentrated on a more general theory of the relations between time series, as seen in Box and Jenkins (1976). For the purpose of this project, it was decided to describe the attenuation and smoothing of the flow in the catchment by an ARMA-type (autoregressive moving average) model.

The ARMA process is

$$Q_t = a_1 Q_{t-1} + a_2 Q_{t-2} + \dots + a_p Q_{t-p} + I_t - b_1 I_{t-1} - b_2 I_{t-2} - \dots - b_q I_{t-q} \quad (2)$$

in which

Q_t, Q_{t-1}, \dots = elements in the output time series,

I_t, I_{t-1}, \dots = elements in the input time series, (transformed to zero mean),

a_1, a_2, \dots, a_p = the autoregressive parameters,

b_1, b_2, \dots, b_q = the moving average parameters,

t = time,

p = the number of autoregressive parameters, and

q = the number of moving average parameters.

Details on the theory of fitting the parameters can be found in Box and Jenkins (1976). Two principal problems are involved: first, the determination of the required number of parameters, and second, the estimation of the parameters themselves.

Identification of the necessary parameters was carried out through analysis of the autocorrelation and the partial autocorrelation functions of the transformed series. According to "Akaike's Information Criterion" (AIC), the number of free parameters which gave a minimum estimate of AIC was determined (Hipel et al., 1977). This AIC function defines the balance between the number of parameters and the corresponding residual variance. AIC is computed from:

$$AIC = -2 \log_{10}(\text{maximum likelihood}) + 2 (\text{number of parameters}) \quad (3)$$

The model parameters were estimated by the maximum likelihood method. The maximum likelihood function was formulated and its maximum obtained by minimizing the residuals between the transformed and measured series applying the so-called Marquardt algorithm. As seen above, the identification of the number of parameters and the estimation of parameters cannot be separated.

MODEL OF OVERFLOW AND RETENTION STORAGE

The output from the ARMA-model was transformed into a model of the retention storage including the overflow. This simple model was based on the continuity equation for the reservoir

$$F(h) \frac{dh}{dt} = Q_i - Q_b - Q_o \quad (4)$$

in which

h = the water depth in the reservoir,

$F(h)$ = the surface area of the reservoir,

Q_i = the input from catchment,

Q_b = bottom outflow $Q_b = k_b h^{1/2}$, and

Q_o = overflow $Q_o = 1.89 k_o (h - h_o)^{3/2}$.

A Runge-Kutta method was used for the integration of Eq. 4.

EXAMPLE

The method has been applied to different catchments, but only one example is shown here. The catchment is situated in Birkerød, a northern suburb of Copenhagen. The catchment data are

Total catchment area	28.9 ha
Average runoff coefficient	0.20
Surface loss on reduced area	0.6 mm
Sewerage discharge	0.005 m ³ /s

The ARMA-model data are

Time increment in numerical model	1 min
Number of autoregressive parameters	$p = 1$
Number of moving average parameters	$q = 4$
Autoregressive parameter	$a_1 = 0.8864$
Moving average parameters	$b_1 = 0.0130$ $b_2 = -0.0426$
	$b_3 = 0.0020$ $b_4 = -0.0120$

The retention storage data are

Bottom surface area	100 m ²
Slope of sides	45°
Weir	Height $h_o = 3$ m, Length $k_o = 2$ m
Bottom outflow constant, k_b	0.02 m ^{5/2} /s
Capacity of sewer after storage	0.08 m ³ /s

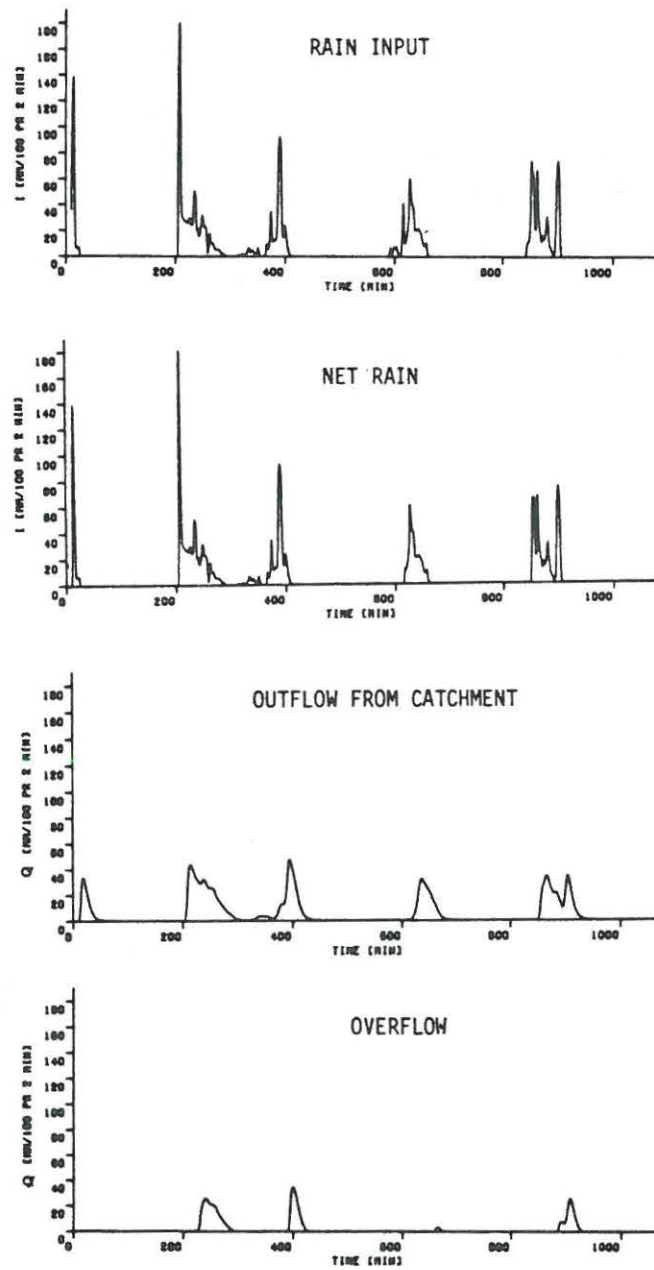


Fig. 1. Example Input and Results

Results from the computer simulation are shown in Figs. 1 and 2. Figure 1 shows a small part of the four time series involved in the simulation and it gives a direct graphical view of the transformations in the computer. Figure 2 gives the statistical results of the simulation where the frequency of overflow volume, overflow duration, maximum (peak) flow and height in retention storage is shown in number of events. The period consists of 29 summer half-years with 1113 storm events.

DISCUSSION AND CONCLUSIONS

Several authors (Eagleson, 1962; Kloet v.d., 1977; Chow and Yen, 1976) have discussed the use of a linear transfer model for the urban runoff process. Although theoretical doubts are numerous, practice shows that such models are reasonably accurate for this purpose. The assumption is that sewer systems do not contain any direct nonlinearity as overflows, pumps etc. But probably the most important but indirect assumption is that the system was previously designed on the basis of a method of the Lloyd-Davies type, which in general gives an oversized system.

The ARMA-filtering suggested here was originally initiated as an interpretation of rainfall/runoff measurements. From the author's point of view it seems to give a balanced compromise between accuracy and computing speed when it comes to the practical use of real rainfall time series for storm sewer design.

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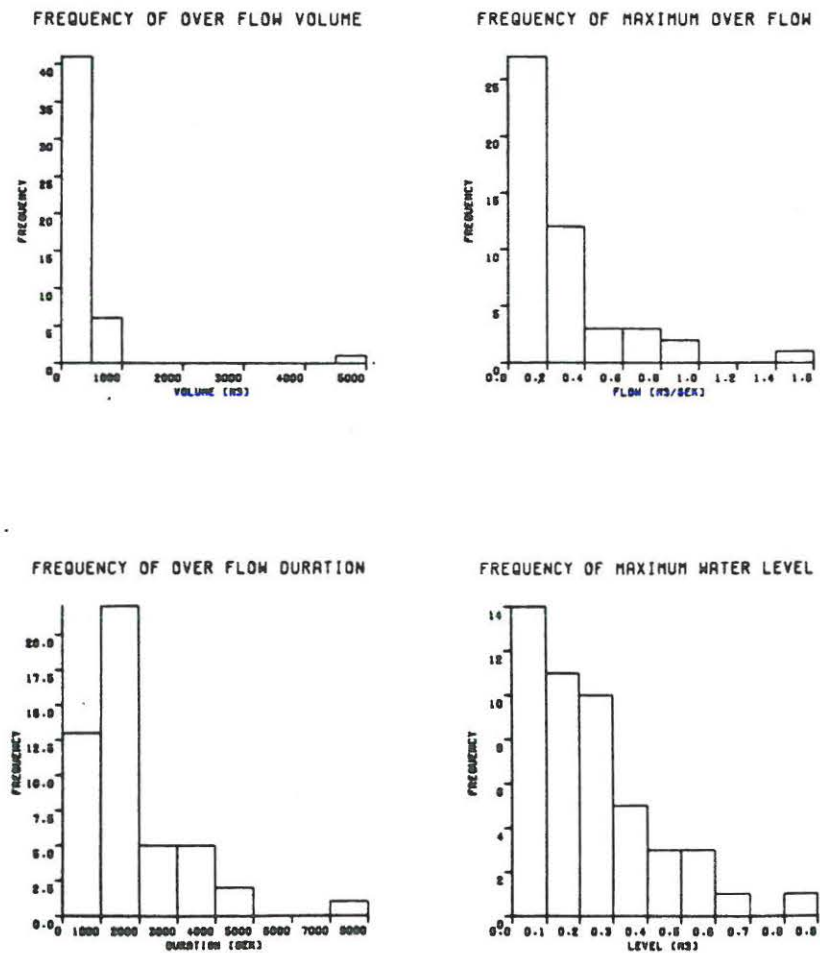


Fig. 2. Simulated Frequency Output